The other side of bulge formation in a Λ cold dark matter cosmology: bulgeless galaxies in the local Universe

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ABSTRACT

We study the physical properties, formation histories and environment of galaxies without a significant 'classical' spheroidal component, as predicted by semi-analytical models of galaxy formation and evolution. This work is complementary to the analysis presented in De Lucia et al., where we focus on the relative contribution of various physical mechanisms responsible for bulge assembly in a Λ cold dark matter cosmology. We find that the fraction of bulgeless galaxies is a strong decreasing function of stellar mass: they represent a negligible fraction of the galaxy population with $M_\star > 10^{12} \, \mathrm{M_\odot}$, but dominate at $M_\star < 10^{10} \, \mathrm{M_\odot}$. We find a clear dichotomy in this galaxy population, between central galaxies of low-mass dark matter haloes and satellite galaxies in massive groups/clusters. We show that bulgeless galaxies are relatively young systems, that assemble most of their mass at low redshift, but they can also host very old stellar populations. Since galaxy–galaxy mergers are assumed to lead to the formation of a spheroidal component, in our models these galaxies form preferentially in low-mass haloes that host a small number of satellites galaxies. We show that the adopted modelling for galaxy mergers represents a key ingredient in determining the actual number of bulgeless galaxies. Our results show that these galaxies are not a rare population in theoretical models: at $z \sim 0$, galaxies with no classical bulge (but often including galaxies with the equivalent of pseudo-bulges) account for up to 14 per cent of the galaxies with $10^{11} < M_\star/\mathrm{M_\odot} < 10^{12}$.

Key words: galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: structure.

1 INTRODUCTION

Since the introduction of the morphological classification scheme by Hubble (1926), two components are traditionally identified in galaxies: a centrally concentrated spheroidal-like structure ('bulge') and a disc-like stellar distribution, often associated with spiral arms. The galaxy population can be (and usually is) classified according to the relative contribution of these two components to the total light emitted by the system. A finer classification takes into account the contribution from other components (e.g. bars, spiral arms). In the last few decades, observational evidence has been gathered to indicate that this picture is oversimplified: bulges (which contribute up to 60 per cent of the stellar mass in massive galaxies in the local Universe; Gadotti 2009) are now seen as a heterogeneous class, including purely spheroidal systems (elliptical galaxies), 'classical' bulges (dynamically and photometrically similar to ellipticals, but with significant kinematical differences; see e.g. Davies & Illing-

worth 1983) and 'pseudo'-bulges (characterized by 'disc'-like exponential profiles or kinematics; see e.g. Kormendy & Kennicutt 2004 and references herein).

Theoretical models predict that early star formation takes place mainly in discs that form due to the conservation of the angular momentum acquired through early torques acting during the protogalactic stage. Bulges form as the result of physical processes able to remove the angular momentum of stars and gas. In particular, classical bulges and purely spheroidal systems are believed to be associated with the most violent dissipative processes, like mergers and close interactions. On the other hand, pseudo-bulges are usually linked to secular evolution of gravitational instabilities in the disc component: the 'unstable' structure is expected to find a new equilibrium following a rearrangement of part of the gas and stars in a central structure with enhanced density. Whenever these processes are infrequent and/or inefficient, we expect the galaxy morphology to be dominated by a disc component. These galaxies are often referred to as 'bulgeless', and have been seen as a potential challenge for current theories of galaxy formation and evolution in a Λ cold dark matter (ΛCDM) universe (see e.g. D'Onghia & Burkert

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2004). Following these suggestions several authors (see e.g. Graham & Worley 2008) used bulge–disc decomposition algorithms to determine the relative contribution of these two components in samples of local galaxies. In particular, Weinzirl et al. (2009) considered a sample of 143 bright ($M_B < −19.3$) low-inclination spirals and found that a relevant fraction (∼66 per cent) of these is dominated by a disc component accounting for more than 80 per cent of their total stellar mass. Starting from a sample of ∼4000 bright ($M_B < −18$) galaxies at $0.013 < z < 0.18$, Cameron et al. (2009) computed a total stellar mass density for pure-disc objects of $1.3 \pm 0.1 \, M_\odot \, Mpc^{-3}$. More recently, Kormendy et al. (2010, K10 hereafter) consider a sample of 19 relatively massive (rotation velocities $V_{rot} > 150 \, km \, s^{-1}$) and close (<8 Mpc) galaxies, and find that four of these are consistent with being pure disc galaxies. Seven galaxies in the same sample [including the Milky Way (MW)] have pseudo-bulges. In total, K10 estimate that 58–74 per cent of the galaxies in their sample do not experience relevant mergers in the past (they include in the bulgeless category those galaxies with a pseudo-bulge). Considering that, at these masses, quiet merger histories are rare, all these authors propose their estimates as a crucial test for galaxy formation models.

The formation of bulgeless galaxies represents a classical challenge also for cosmological *N*-body hydrodynamical simulations. If conserved during its collapse towards the centre of the galaxy, the angular momentum of the gas is sufficient to produce large discs (e.g. Fall & Efstathiou 1980; Mo, Mao & White 1998). Cooling in small and dense progenitors at high redshift, however, condenses the gas in their inner regions. Dynamical friction on the orbiting satellites then dissipates the gas angular momentum (e.g. D'Onghia et al. 2006). As a result, discs in *N*-body simulations are too compact (with rotation curves that usually peak at a few kpc) with respect to observational measurements (Steinmetz & Navarro 1999; see Mayer, Governato & Kaufmann 2008 for a review). One of the proposed (and so far most successful) solution to the angular momentum 'catastrophe' requires a fine tuning of the feedback in small high-redshift progenitors so as to avoid early gas cooling (e.g. Governato et al. 2010). It should be noted that loss of angular momentum is caused also by secular evolution of discs and bar instability (see e.g. Debattista et al. 2006), and that these are more easily triggered in discs that are made compact by partial loss of angular momentum (Curir, Mazzei & Murante 2006).

In a recent paper, De Lucia et al. (2011, hereafter Paper I) analyse the predictions from semi-analytical models (SAMs) of galaxy formation and evolution within a ΛCDM cosmology, and quantify the relative contribution of different processes (major and minor mergers, and disc instabilities) to the assembly of bulges. In this paper, we will tackle a complementary question, i.e. determine under which conditions a model galaxy does *not* develop a significant spheroidal component.

2 MODELS

In this paper, we present predictions from two independently developed SAMs, namely the Wang et al. (2008, hereafter WDL08) implementation of the 'Munich' model and the MORGANA model, as adapted to the *Wilkinson Microwave Anisotropy Probe 3* cosmology in Lo Faro et al. (2009). We refer to the original papers for a detailed discussion of the models used in this study, and to Paper I for a detailed description of the recipes adopted to model bulge formation. In this section, we provide a brief summary of these ingredients.

Both models consider similar channels leading to the assembly of a spheroidal component, namely galaxy–galaxy mergers and

disc instabilities. There are, however, significant differences in the treatment of these processes. In both models, *major mergers* completely destroy the disc components of the two galaxies. The remnant spheroidal galaxy may eventually regrow a disc, if fed by an appreciable cooling flow at later times. During *minor mergers*, both SAMs assign the stellar component of the secondary galaxy to the bulge of the remnant, but make different assumptions about the stars formed during the burst associated with the merger: the WDL08 model gives them to the disc of the remnant galaxy, while the MORGANA model gives them to its bulge. This different choice implies that the contribution of minor mergers to bulge assembly is more important in MORGANA. De Lucia et al. (2010) compared the merger models implemented in MORGANA and WDL08 and found that the former provides *merger times* that are systematically shorter than those used in the latter (by about an order of magnitude): this translates into a higher frequency of merger events in MORGANA and has important consequences for the timing of bulge formation, as discussed in Paper I. In particular, due to the shorter merger times and the different treatment of minor mergers, we have shown that MORGANA predicts a larger stellar mass locked in bulges at each redshift, and larger mean bulge-to-total mass ratios (B/T) for galaxies of all masses.

The two models used in this study also differ in their treatment of *disc instabilities*: both models adopt the stability criterion defined in Efstathiou, Lake & Negroponte (1982), but use different definitions for the relevant physical quantities (in particular disc velocities and radii; see section 7 and fig. 10 of Paper I). In addition, they make different assumptions about the rearrangement of baryons following instability events: in WDL08 only the stellar mass fraction necessary to restore stability is transferred from the disc to the bulge. In MORGANA, a significant fraction (i.e. half) of the baryonic mass (both gas and stars) of the disc is transferred to the bulge. As shown in Paper I, the approach adopted in the MORGANA model translates into a more prominent role of the disc instability channel in bulge formation.

Following Paper I, we consider in the following three different implementations for each model: a *standard* implementation, which includes both mergers and disc instability, a *pure merger* implementation where we switch off the disc instability channel, and a model that adopts the Hopkins et al. (2009, HOP09 hereafter) prescriptions for the redistribution of gas and stars during mergers, and for modelling the fraction of disc material which survives merger events. Briefly, the HOP09 approach reduces the efficiency of bulge formation and increases the fraction of baryonic mass in disc components at each redshift. In addition, it assumes that a fraction of the disc survives even during major mergers. In Paper I, we showed that this change has important consequences for the predicted space density of purely spheroidal (elliptical) galaxies, but it does not affect bulge formation in galaxies less massive than $\sim 10^{10} \, M_\odot$.

Our SAMs do not allow a fine classification of the different bulge subclasses to be made. In particular, it is not possible to disentangle between the formation of a pseudo-bulge and classical bulge, based just on the properties of the final spheroidal component. None the less, our strategy provides a natural framework for the analysis presented in this study: assuming that classical bulges are associated with mergers, and that pseudo-bulges originate from instabilities, the standard implementation gives the full statistics for disc-dominated galaxies, while the comparison with the pure merger implementation provides information about the relative contribution of classical and pseudo-bulges.

In this paper we will define as 'bulgeless' all model galaxies with a B/T lower than 0.1, i.e. all model galaxies whose bulges

contribute to less than 10 per cent of their total stellar mass. In the following, we consider only galaxies with $M_\star > 10^9 \, \mathrm{M_\odot}$, which is above the resolution limit of our simulations. Resolution effects may play a role in our definition of bulgeless galaxies, especially for galaxies with $M_\star < 10^{10} \, \mathrm{M_\odot}$, since we are not able to account for mergers with and between lower mass galaxies. We note, however, that galaxy formation in lower masses haloes is an increasingly inefficient process (see e.g. Benson & Devereux 2010). So minor mergers with small galaxies hosted in subresolution haloes are not expected to contribute much to the growth of the central spheroid, and to affect the results discussed below.

3 RESULTS

In this section, we will discuss in detail the properties, environment and formation history of bulgeless galaxies, as predicted by our SAMs. In particular, we consider the fraction $f_{\mathrm{bl}}(P)$ of model galaxies with $B/T < 0.1$ and with a given property P, and the normalized (to the total number of systems) distribution $n_{\mathrm{bl}}(P)$ of bulgeless galaxies as a function of P.

Fig. 1 shows $f_{\mathrm{bl}}(M)$ as a function of stellar mass ($M_\star$) and parent halo mass (M_{DM}). In each panel, the red, blue and green histograms refer to the standard, pure merger and HOP09 implementations, respectively. The shaded histograms show the contribution of central galaxies (same colour coding). Common trends between the two SAMs and the three implementations considered can be seen. In the standard runs, $f_{\mathrm{bl}}(M_\star)$ exhibits a marked decrease as a function of $M_\star$ (left-hand panels). A similar result is obtained in the pure merger runs, although in this case the resulting fractions are larger than those obtained in the standard models, because of the lack of bulges forming via the disc instability channel. Neglecting bulge formation via disc instabilities has a stronger effect on predictions from MORGANA than on those from WDL08. This is due to the more

efficient mass transfer associated with this physical mechanism in the former model. At all masses, $f_{\mathrm{bl}}(M_\star)$ in WDL08 is larger than in MORGANA for both implementations: this is due to the assumption of shorter merger times in MORGANA, which leads to a more efficient bulge formation in this model with respect to WDL08. Therefore, the relatively small $f_{\mathrm{bl}}(M_\star)$ in the standard MORGANA run is due to a combination of shorter merger time-scales, and stronger mass transfer via disc instabilities. We test explicitly the influence of different merger times, by rerunning MORGANA using the same dynamical friction prescription adopted in WDL08 – results are shown as a black solid line in the bottom panels of Fig. 1. As expected, when longer merger times are assumed, $f_{\mathrm{bl}}(M)$ increases because more galaxies are able to avoid mergers.

We find that the HOP09 implementations do not alter significantly the fraction of bulgeless galaxies with respect to the runs considered above: this is consistent with conclusions from our Paper I that this recipe does not affect bulge formation in galaxies less massive than $\sim 10^{10} \, \mathrm{M_\odot}$. We note, however, that the HOP09 predictions for the WDL08 model are closer to the standard results, while for MORGANA they are closer to the pure merger model results. This difference is due to the different treatment of the stars associated with bursts triggered by minor mergers: as explained above, these are given to the disc of the remnant galaxy in the standard implementation of the WDL08 model, while when adopting the HOP09 recipes this model assumes (as done in the MORGANA model) that these stars go to the bulge of the remnant galaxy.

We then consider the fraction of bulgeless galaxies as a function of their parent halo mass [$f_{\mathrm{bl}}(M_{\mathrm{DM}})$, right-hand panels]. A clear dichotomy in the bulgeless population can be seen: lower mass haloes have an increasing probability of hosting a central bulgeless galaxy (larger than 70 per cent for $M_{\mathrm{DM}} < 10^{11} \, \mathrm{M_\odot}$), while almost all central galaxies of haloes with $M_{\mathrm{DM}} \gtrsim 10^{12} \, \mathrm{M_\odot}$ host significant bulges in all implementations. On the other hand, bulgeless satellites constitute an important fraction of cluster/group galaxies. MORGANA predicts a lower $f_{\mathrm{bl}}(M_{\mathrm{DM}})$ and a clear dip at $M_{\mathrm{DM}} \sim 10^{12} \, \mathrm{M_\odot}$ (depending on the chosen implementation). For the WDL08 model the trends as a function of the halo mass are somewhat weaker.

In order to compare the results shown in Fig. 1 with the K10 data, we have computed the galaxy stellar mass for all galaxies in the K10 sample. In particular, we have used table B1 from Zibetti, Charlot & Rix (2009), the K-band magnitudes given in K10, and $(B - V)_0$ colours obtained using the HyperLeda data base (Paturel et al. 2003). Given the tight relation between the stellar mass of central galaxies and their parent halo mass, we expect this approach to be consistent with the K10 analysis (which is based on rotation velocities), and it provides a more straightforward comparison with our theoretical predictions. We thus compute the fractions of bulgeless galaxies $f_{\mathrm{bl}}(M_\star)$ in two mass bins ($10^{10} < M_\star/\mathrm{M_\odot} < 10^{11}$ and $10^{11} < M_\star/\mathrm{M_\odot} < 10^{12}$), by using the B/T ratios listed in K10 (see their table 2). We give our estimated fractions in Table 1, together with the Wilson score intervals[1] calibrated at the 95 per cent confidence limit.

In order to take into account the error due to cosmic variance, we consider all central galaxies living in MW-type haloes ($10^{12 \pm 0.25} \, \mathrm{M_\odot}$) in the WDL08 model, and define K10-like samples in the mass range $10^{10} < M_\star/\mathrm{M_\odot} < 10^{12}$ by considering all galaxies closer than 8 Mpc. We then compute the median $f_{\mathrm{bl}}(M_\star)$ value and
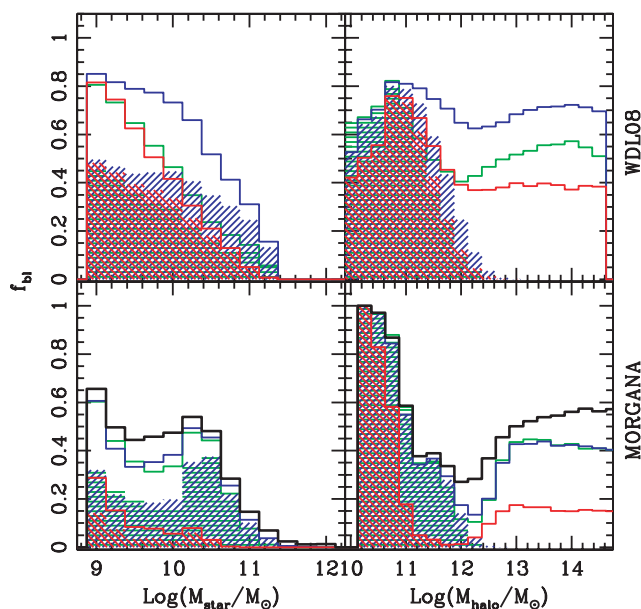

Figure 1. The fraction of bulgeless galaxies (f_{bl}) as a function of their stellar mass and parent halo mass. In each panel, red, blue and green lines refer to the standard model, the pure merger implementation and the HOP09 implementation, respectively. Shaded histograms are for central galaxies, and the same colour coding are used. In the panels showing results from MORGANA, the thick solid black line shows results obtained adopting longer merger times (see text for more details).

[1] The Wilson (1927) approximation provides an estimate for asymmetric errors based on confidence levels of a binomial distribution, which is more appropriate than a normal distribution for small number statistics.

Table 1. Predicted and observed fractions $f_{bl}(M_\star)$ of bulgeless galaxies around MW-like haloes. Theoretical predictions refer to the median $f_{bl}(M_\star)$ value, with the confidence levels defined on the fifth and 95 th percentiles of the distribution, while confidence levels for the K10 data are based on the Wilson score interval approximation.

	$10^{10} < M_\star/\mathrm{M_\odot} < 10^{11}$ (per cent)	$10^{11} < M_\star/\mathrm{M_\odot} < 10^{12}$ (per cent)
Standard implementation		
WDL08	26^{+13}_{-9}	0^{+14}_{-0}
K10 (total bulges)	60^{+26}_{-33}	27^{+25}_{-16}
Pure mergers implementation		
WDL08	57^{+11}_{-8}	14^{+52}_{-14}
K10 (classical bulges)	80^{+15}_{-36}	55^{+21}_{-23}

its confidence interval based on the fifth and 95 th percentiles of the distribution. This analysis is limited to the WDL08 model because MORGANA does not predict accurate positions for satellite galaxies. In Table 1, we compare predictions for the standard WDL08 run with the fraction of disc galaxies in K10 sample (i.e. galaxies with total $B/T < 0.1$), and predictions obtained from the pure merger model with the fraction of galaxies with no classical bulge defined in K10 (i.e. classical $B/T < 0.1$). The theoretical fractions are systematically lower than observations, and the discrepancy is severe for the standard implementation compared to the distribution of pure discs: the probability of observing a sample with the same morphological mix measured by K10 is smaller than 1 per cent in the volume of the simulation used by the WDL08 model. The discrepancy between theoretical predictions and observational estimates is, however, reduced if we consider the predictions for the pure merger runs and compare them to the fraction of galaxies without a classical bulge: in this case, the probability of finding an MW-like neighbourhood similar to the K10 sample is larger than 5 per cent. We note that when selecting MW-like haloes, we have not applied any isolation criterion, which could further increase the expected fraction of bulgeless systems. If pseudo-bulges can be associated with secular processes, our results clearly show the importance of the adopted modelling of disc instabilities in order to correctly estimate the expected $f_{bl}(M)$.

We also compare predictions from theoretical models with the observational estimates of Weinzirl et al. (2009) and Cameron et al. (2009) who compiled samples that are larger than that of K10. However, the Weinzirl et al. (2009) sample is not mass and volume complete due to less well-controlled selection criteria, while the Cameron et al. (2009) decompositions suffer a number of additional problems, due to poorer resolution of higher redshift objects: in fact we note that accurate decomposition of galaxies is difficult, becoming worse at low resolution (e.g. higher z) and where fewer components are included (e.g. bars; see Laurikainen et al. 2007). In addition, an accurate comparison with these samples would require additional sources of uncertainties in our model predictions, such as the inclusion of dust attenuation and the modelling of synthetic spectral energy distributions.

None the less, we make a qualitative comparison between data and models, by defining a mass-selected sample of $M_\star > 10^{10}\,\mathrm{M_\odot}$ model galaxies, which roughly corresponds to the mass range covered by observations. We find the following $z = 0$ total stellar mass densities for $B/T < 0.1$ galaxies: 0.3×10^8 and $0.9 \times 10^8\,\mathrm{M_\odot\,Mpc^{-3}}$ (for the standard and pure merger implementations of the WDL08 model, respectively) and 0.03×10^8 and $0.6 \times 10^8\,\mathrm{M_\odot\,Mpc^{-3}}$ (for the standard and pure merger implementations

of MORGANA model, respectively). These numbers are lower than those found by Cameron et al. (2009; $1.3 \pm 0.1 \times 10^8\,\mathrm{M_\odot\,Mpc^{-3}}$).

Using the same sample of model galaxies, we compare the predicted fraction of $B/T < 0.2$ high-mass spirals with the Weinzirl et al. (2009) results ($\sim$66 per cent; following that paper, we define spirals as galaxies with $B/T < 0.75$). These galaxies account for 18 per cent (67 per cent) of objects in the standard (pure merger) implementation of the WDL08 model, and for 49 per cent (81 per cent) of objects in the standard (pure merger) implementation of MORGANA. These estimates confirm our conclusion that bulgeless galaxies are underpredicted by the standard implementations of SAMs. The discrepancy is, however, sensibly reduced when pure merger implementations of the same models are considered.

In a recent publication, Fisher & Drory (2011) analysed the fraction of classical and pseudo-bulges in the local volume (closer than 11 Mpc). We repeat our analysis on $f_{bl}(M_\star)$, using this new sample and the same approach as for the K10 sample (Fig. 2). From the Fisher & Drory (2011) data (their table 1), we draw two subsamples including galaxies with both total $B/T < 0.1$ (solid line and grey shaded region) and classical $B/T < 0.1$ (dashed line; we consider all galaxies showing a prominent pseudo-bulge component as bulgeless), and we compare them with the prediction of the standard (red diamonds with error bars) and pure merger (blue diamonds with error bars) implementations of the WDL08 model, respectively. Samples of model galaxies are defined within 11 Mpc from central galaxies of MW-like haloes, and we compute the mean $f_{bl}(M_\star)$ and its confidence interval based on the fifth and 95 th percentiles of the distribution. In both cases, model predictions underpredict the observational results; however, the discrepancy between the standard implementation and the $f_{bl}(M_\star)$ based on the total $B/T < 0.1$ ratio is reduced with respect to the K10 sample. The agreement between the pure merger implementation and the sample based on the classical $B/T < 0.1$ is satisfactory. We note that theoretical
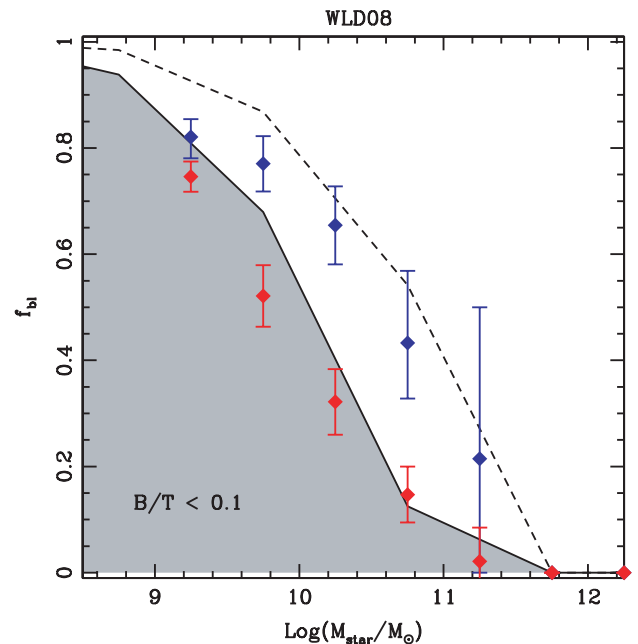

Figure 2. The fraction f_{bl} of bulgeless galaxies as a function of stellar mass. Observational constrains from Fisher & Drory (2011) data are shown as solid (total $B/T < 0.1$) and dashed lines (classical $B/T < 0.1$), while red and blue dots refer to the standard and pure merger implementations of the WDL08 model (see text for more details).

predictions obtained when considering the entire simulation box are very close to the mean shown in Fig. 2. It is also worth mentioning that the Fisher & Drory (2011) sample contains a significant number of galaxies hosting a pseudo-bulge and with total $B/T > 0.3$ (they account for $\sim$10 per cent of the whole sample of galaxies hosting a pseudo-bulge). Theoretically, we expect that such prominent pseudo-bulges may hide a subdominant (hence relevant) merger-driven classical bulge component and this effect would reduce the discrepancy between the dashed line and blue diamonds.

In order to provide limits on the number of mergers suffered by bulgeless galaxies, we take advantage of the merger histories provided by our models. In particular, for each galaxy in the model, we define a number of 'effective satellites' ($N_{\rm sat}$) as the number of satellite galaxies in its parent halo, computed at the redshift when it (its main progenitor) was for the last time a central galaxy. We only consider satellite galaxies with $M_\star > 10^9\,{\rm M_\odot}$. For central galaxies, the number of effective satellites corresponds to the number of actual satellites. We show $f_{\rm bl}(N_{\rm sat})$ in Fig. 3 (upper panels). We note that the probability of being bulgeless increases with decreasing $N_{\rm sat}$. The figure shows that MORGANA exhibits a very skewed distribution towards low $N_{\rm sat}$ values, while the corresponding distribution for WDL08 is flatter. This is a consequence of the different merger times adopted in the two models, as confirmed by the solid thick line in the right-hand panels that correspond to a run of the MORGANA model (the pure merger run) with longer merger times. Since MORGANA assumes (in its standard implementation) quite short merger times, only galaxies living in very isolated environments survive as bulgeless systems. The WDL08 model adopts longer merger times, so that also galaxies living in haloes with more substructures may avoid developing a significant bulge. Disc instabilities do not change the distributions, but as expected, they affect the fraction of bulgeless galaxies. We stress that, despite a wider range of allowed halo merger histories for bulgeless galaxies in WDL08, the distribution of $n_{\rm bl}(N_{\rm sat})$ (lower panels) is peaked towards very small $N_{\rm sat}$ values.
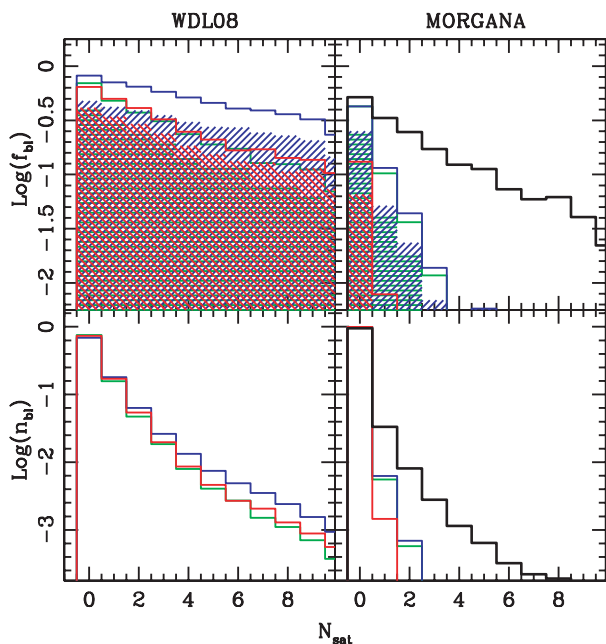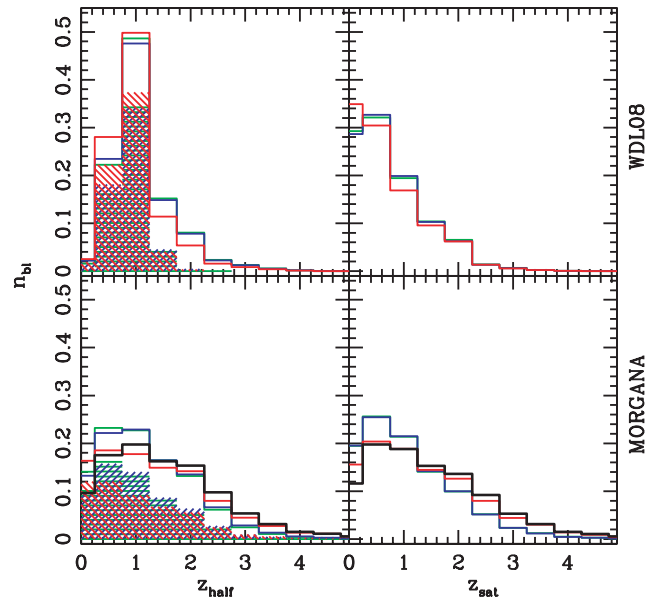

Figure 4. Left-hand panel: the distribution of formation redshifts of bulgeless galaxies (see text for more details). Right-hand panel: the distribution of accretion redshifts for bulgeless satellites. In each panel, colours, lines and shadings are the same as in Fig. 1.

In order to better characterize the physical properties of bulgeless galaxies as predicted from our models, we consider the quantity $z_{\rm half}$, defined as the redshift at which half of the final stellar mass is assembled in a single object. Since mergers play a small role in the assembly of bulgeless galaxies, this quantity is also a good indicator for the star formation history of the galaxy (i.e. it is a good approximation of the time when half of the stars were *formed*). The distribution of $z_{\rm half}$ predicted by our models is shown in Fig. 4 (left-hand panels), and shows that bulgeless model galaxies correspond to a relatively young population: central galaxies are more skewed towards low $z_{\rm half}$ with respect to satellites. These results are consistent with recent observations of the central regions of M33, which appear to be dominated by an old stellar population ($\geq$6 Gyr; Javadi, van Loon & Taghi Mirtorabi 2011) It is also worth noting that these objects contain a significant fraction of old stars in their discs: the presence of 9–10 Gyr old stars in a MW-like galaxy is not unusual. Removing disc instabilities or using the HOP09 merger prescription does not modify significantly the $z_{\rm half}$ distribution: this is due to the paucity of bulge-forming events in the bulgeless galaxies' history. We also consider the distribution of accretion redshifts for the bulgeless satellites ($z_{\rm sat}$, Fig. 4 right-hand panels): here we define $z_{\rm sat}$ as the last time the galaxy is the central object of an independent DM halo. It is worth stressing that this definition does not always correspond to the redshift when the satellite is accreted on to the main progenitor of its $z = 0$ parent halo. Nevertheless, since $z_{\rm sat}$ the star formation history of satellite galaxies is strongly affected by the strangulation in both models. The figure shows that the overall $z_{\rm sat}$ distribution is broader than the $z_{\rm half}$ one. Therefore, both models predict a population of pure red discs in groups and clusters, dominated by quite old stellar populations, which have been accreted as satellites and have stopped forming stars relatively recently.

4 DISCUSSION AND CONCLUSIONS

In this paper we study the statistics, distributions and formation histories of galaxies with $B/T < 0.1$, as predicted by theoretical

Figure 3. Upper panels: $f_{\rm bl}$ as a function of the number of effective satellites (see text for more details). Lower panels: $n_{\rm bl}$ as a function of the number of effective satellites. In each panel, colours, lines and shadings are the same as in Fig. 1.

models in the ΛCDM framework. This is the second paper of a series: in the first paper (Paper I), we have studied the formation of spheroids, and in a third paper we will focus on a detailed comparison between model predictions and observational data (Wilman et al., in preparation).

We consider two independently developed SAMs: the WDL08 implementation of the 'Munich' model and the most recent implementation of MORGANA (Monaco, Fontanot & Taffoni 2007). In addition, we consider three different implementations of each model: a standard run, a pure merger model and a modified merger model based on the prescriptions proposed by HOP09 and on recent hydrodynamical simulations of galaxy mergers. The two models used in this study include the same channels for bulge formation (i.e. galaxy–galaxy mergers and disc instabilities).

Our results highlight that models predict a non-negligible fraction of bulgeless $M_\star < 10^{11}$ M$_\odot$ galaxies at $z \sim 0$. For all models and implementations considered, the fraction of bulgeless galaxies decreases rapidly with increasing stellar mass, and becomes negligible for $M_\star > 10^{12}$ M$_\odot$. Bulgeless galaxies are either central galaxies in low-mass haloes or satellites in groups and clusters. They assemble their mass at relatively low redshifts, but they can host quite old stellar populations. Given our assumption that bulges form during mergers, these galaxies are bulgeless because they had a relatively quiet merger history. Therefore, bulgeless galaxies are more likely to form in dark matter haloes hosting few satellites, where galaxy merger rates are low enough to assure that the merger channel is inefficient in forming a large bulge. The comparison between results of the two models highlights the importance of the assumed prescription for merger times (see also De Lucia et al. 2010).

We compare our model predictions with observational results from the K10 sample. The most interesting discrepancy between models and data is found for galaxies with $10^{10} < M_\star/$M$_\odot < 10^{12}$, where the fraction of bulgeless galaxies predicted by theoretical models is systematically lower than the observational estimate. The discrepancy is significant when comparing predictions from the standard model to the observed fraction of 'pure discs'. On the other hand, the predictions of the pure merger implementations of our SAMs are statistically consistent (within 95 per cent confidence level) with the observational estimates, if we classify as bulgeless also galaxies with a relevant pseudo-bulge (as done in the study by Kormendy et al.). Our results show that model galaxies without a classical bulge are not rare: they can account for up to 14 per cent of the total mass budget of galaxies in the range $10^{11} < M_\star/$M$_\odot < 10^{12}$. Our conclusions are confirmed by the quantitative comparison with recent results by Fisher & Drory (2011), and by a qualitative comparisons of model predictions with larger galaxy samples defined in Weinzirl et al. (2009) and Cameron et al. (2009). These results are in line with previous studies in showing the importance of the adopted modelling of disc instability to account for the estimated B/T of our own MW (De Lucia & Helmi 2008; Macciò et al. 2010).

We note that our conclusions depend on the assumed B/T threshold for the definition of bulgeless galaxies. In particular, the fraction of bulgeless galaxies decreases when adopting a lower threshold (and vice versa). However, for $10^{10} < M_\star/$M$_\odot$ and $M_\star/$M$_\odot > 10^{12}$ our results do not significantly change when varying the adopted threshold. This means that, for decreasing B/T thresholds the slope of the $f_{bl}(M_\star)$ distribution increases, and the $n_{bl}(N_{sat})$ distribution becomes more skewed towards low N_{sat} values. Redshift distributions are unaffected. The choice for the B/T threshold may thus represent an important aspect of our comparison between data and model predictions. Given the observational uncertainties in the bulge/disc

decomposition (e.g. Laurikainen et al. 2007; Tasca & White 2011), we believe that our $B/T < 0.1$ choice is a reasonable one.

The main result of this paper is that SAMs predict enough merger-quiet galaxies to be (almost) consistent with the dearth of classical bulges in the local Universe. In particular, we find that the claimed tension between observational estimates based on the local volume and predictions from SAMs weakens considerably when (i) disc instability is switched off leaving mergers as the only channel to create bulges in models and (ii) only classical bulges are considered in the data. Some caveats should be considered. The theoretical models adopted in this paper are tuned to reproduce the observed fraction of stellar mass locked in bulges at $z \sim 0$. If the instability channel is switched off, these models might underproduce the stellar mass in bulges with respect to the observational estimates. In addition, as discussed extensively in Paper I, our modelling of disc instability is very simplistic which has important consequences for the formation and statistics of bulges.[2]

The models considered here do not predict the detailed properties of discs (other than baryonic masses and scalelengths), and they assume no angular momentum dissipation, i.e. perfect conservation of the angular momentum imprinted in the baryonic components (usually modelled assuming some realistic distributions derived from numerical simulations). Simulations show that this approach is probably oversimplified, and that also haloes with a quiet merging history acquire only a fraction of the angular momentum required for rotational support by tidal torques (see e.g D'Onghia & Burkert 2004).

Finally, model bulges assemble their mass as the result of both mergers and disc instabilities. Given the assumed tight connection of classical (pseudo-) bulges with mergers (disc instabilities), we expect bulges to be composite systems. The K10 sample that we have used in this study contains a relevant population (five out of 19) of galaxies hosting a relatively large $(0.1 < B/T < 0.4)$ pseudo-bulge, and with no evidence of a classical component. In order to use these observations to constrain model predictions, it is of critical importance to determine to which extent a massive pseudo-bulge may hide a classical component and vice versa. The results of Gadotti (2009) suggest that 'composite' (actually classical bulges with signs of star formation activity) bulges are indeed common in the local Universe: unfortunately, the decomposition of a galaxy's photometry into the contribution of different components is a challenging task, and an unambiguous separation of classical and pseudo-bulges is currently possible only at low redshift (see also Tasca & White 2005). Advances in this field will enable us to increase our knowledge of the complex interplay of the physical mechanisms responsible for the distribution of observed galaxy morphologies.

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[2] It is worth mentioning that the Bower et al. (2006) model, which is not considered in this work, adopts yet different assumptions for instabilities: at each instability event, the whole disc is destroyed and all its baryons are given to the spheroidal component.

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